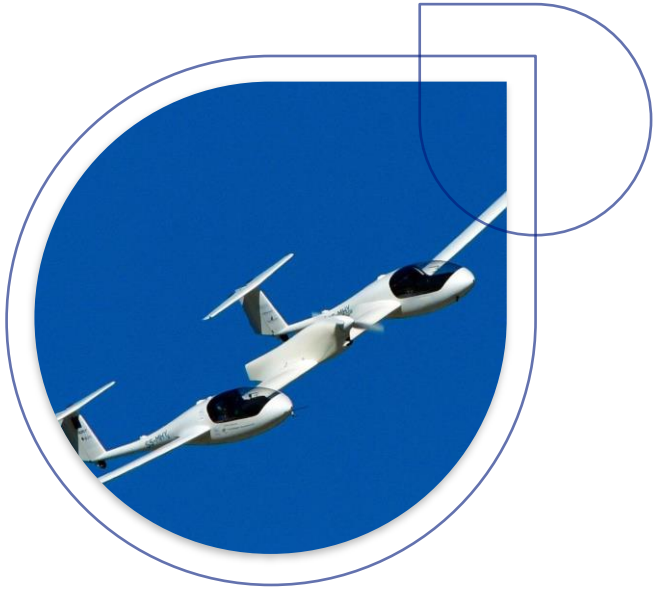
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, Sept 2024. Presentation given at ICEC-ICMC 2024, July 2024, Geneva, Switzerland.

Air Liquide

Cryogenics for power and energy : a winning ticket?



Pierre Crespi, Head of Innovation
Air Liquide advanced Technologies

ICEC/ICMC

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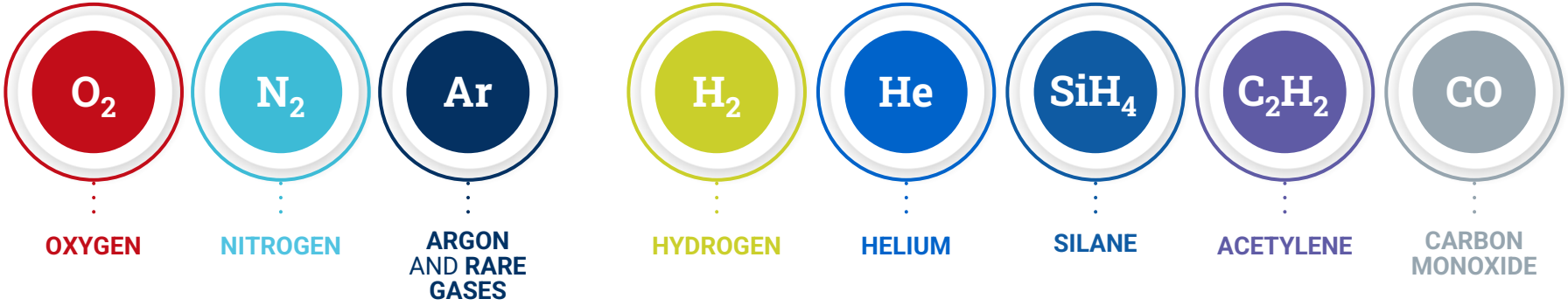
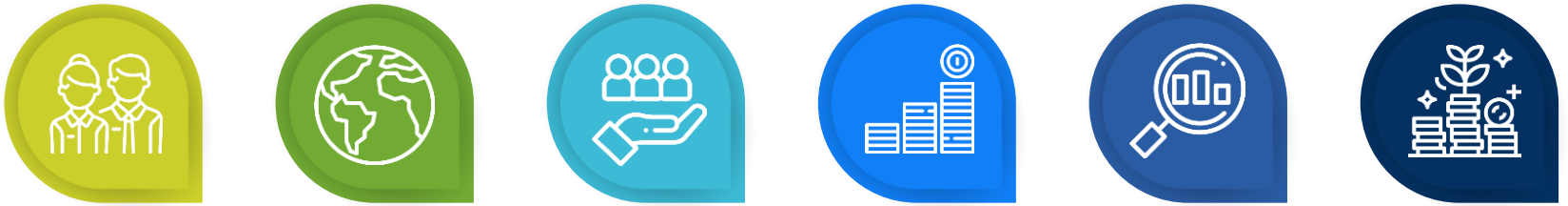
Air Liquide : a world leader in industrial & medical gases

Created in 1902 for air liquefaction : cryogenics is our essence!





~67,800
EMPLOYEES

PRESENT IN 72
COUNTRIES

MORE THAN 4 MILLION
CUSTOMERS & PATIENTS

REVENUE
€27.6bn

NET PROFIT
(GROUP SHARE)
€3.1bn

INVESTMENT DECISIONS
~€4.3bn

Cryogenics is becoming an enabler for the energy transition

Generating electrical power : LTS & HTS **High Magnetic Field**

- **Fusion** (magnetic confinement)
- **Offshore wind power** (10-20 MWe turbines)

Transporting electrical power : HTS @ 20K - 65 K **2000 to 10 000 A, 0 Tesla**

- Technologies available : **piping** ; **REBCO superconductors** ; **large refrigerators**
- Typically : **1 GW over 100 km ~ 1 MW @ 65 K**

Producing, storing, distributing energy with cryogenic liquid carriers

- **LNG Boil-Off :** on ships > 80 000 tons
- **LH2 liquefier:** 10 tons/day ⇒ 100 tons/day
- **LH2 storage :** rockets (30 t) trucks (0,1 t) aircraft (1 t) ships (10 – 10 000 t)

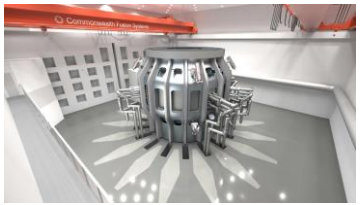
A broad market outlook for cryogenics in the energy transition

Nuclear fusion market looks promising for cryogenics

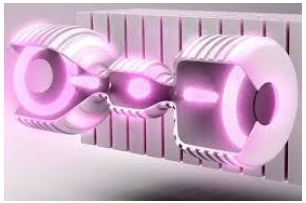
(as said by C Senatore in *Advancing Superconductor Technology for High Field Applications*, ICEC-ICMC-2024)

45 private companies on fusion* (25 in US)

- $7,1 bn funding (94% private)
- Many use HTS for magnetic confinement
- May emulate an agile SpaceX-type model
- Might generate electricity in the 2030s



SPARC @ 8 K (in US)
Commonwealth Fusion Systems (US)



Inductive fusion
Helion (US)

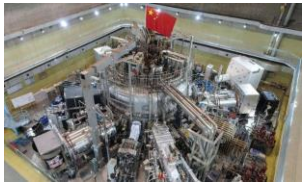
* Source : Fusion Industry Association - FIA 2024

Many institutional projects

- Large TOKAMAK-type
- LTS required (so far)

ITER
(34 countries, in France)

JT60-SA
(Japan)



EAST then BEST
(China)

CFETR
(China)

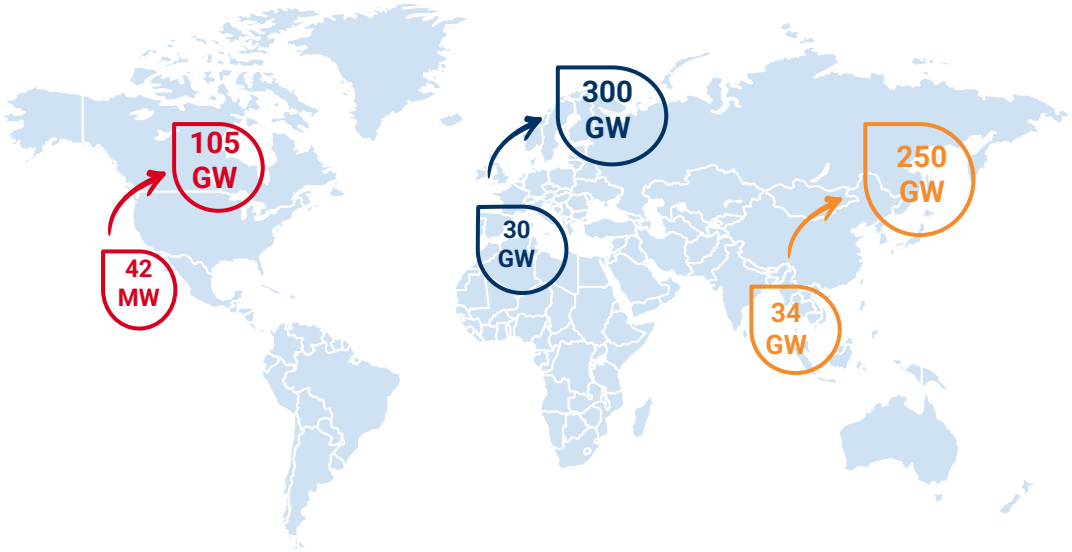
Offshore wind power market is also promising for superconductivity

Figures from 2023 to 2040

More than 500 GW new offshore wind capabilities

30 000 to 50 000 wind turbines to be installed (10-20 MW each)

Hundreds of long range underwater transmission lines



Superconductivity may address some of the challenges :

- **shortage of RE** (for PMs in generators)
- **cost and deployement of many large HVDC converters** for long range power transmission (offshore and onshore)

LH2-powered heavy duty vehicle market : cryogenics as an enabler

A good regulatory framework is in place for trucks

Many OEMs have clear development roadmaps

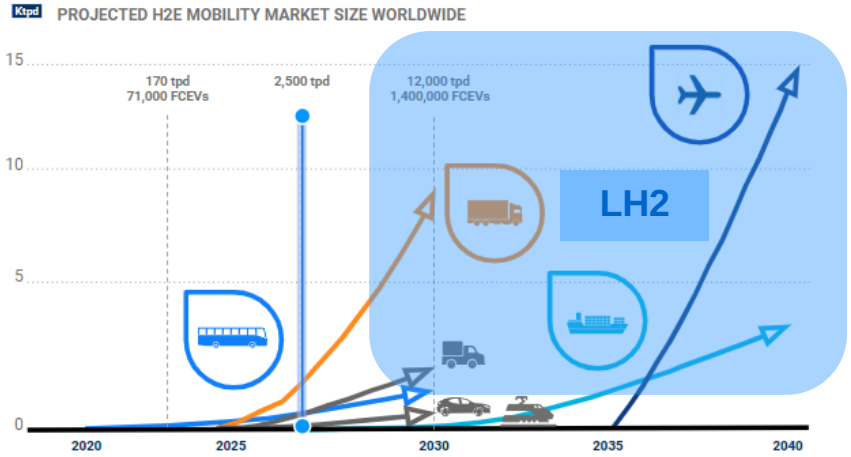
- Producing 1000 H2-trucks/year per OEM is feasible

Liquid H2 more efficient than gaseous H2 for long range trucks > 1000 km, 80 kg of H2

About 2 X 40 kg LH2 tanks needed per truck

- Subcooled state (sLH2 *) = good management of boil-off
  Allows fast refueling

Challenges : Mass production LH2 tanks, deployment of liquid H2 Refueling Stations and liquefiers



2030 : 12 000 tpd demand
Current ww LH2 capabilities ~ 450 tpd, 43 plants
Announced liquefier projects : > 4000 tpd (60% in APAC)

(*) see: *Cryogenic H2 for HDV : Applying Fundamental Thermodynamics to Solve CleanTransportation Challenges,* Petitpas and al. ICEC2024

tpd : tons per day

Consequences : a lot of demand on cryogenics for liquid H2

Liquefaction : - Air Liquide is operating its 30 tpd(*) liquefier in Las Vegas

- 3 X 30 tpd just built for SK Group in Korea, more to come

30 tpd = 10 MWe (incl. precool.), 250 kW@20K

On board **storage** for aircraft (HEAVEN flight in 09/2023) and trucks (FORVIA - Air Liquide partnership)

Liquid H2 **refueling** stations (HRS):

- HRS to be supplied with LH2 even for GH2-powered FCVs
- HRS will also deliver LH2 or SH2 to heavy duty vehicles (1st LH2 station by Air Liquide for DAIMLER)

(*) FCV : Fuel Cell Vehicle

Technologies required for the energy transition :

Cryogenic liquefiers and refrigerators

Liquefaction of Hydrogen

Pre-cooling down to 80 K with either :

- LN2, Mixed Refrigerant Cycles (MRC) or turbo-Brayton

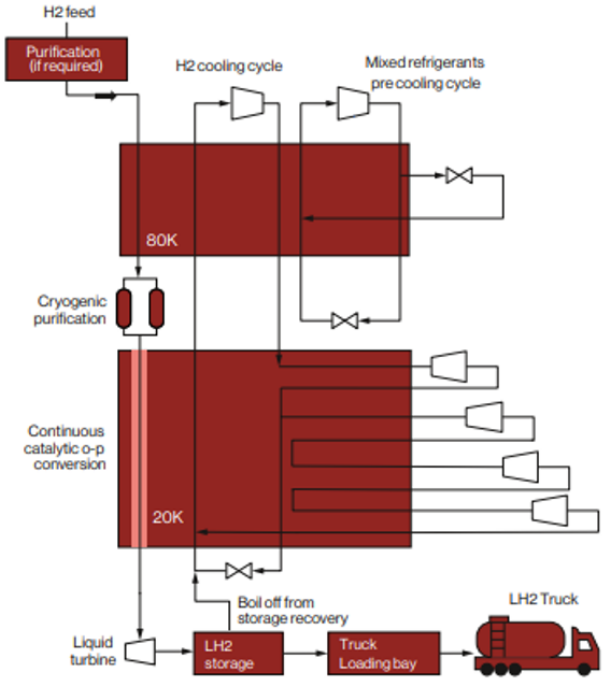
Piston-type compressors (~8-10 MW for 30 tpd)

A cascade of 4 cryogenic turbo-expanders
in the 20 K cold box

Boil-off from storage & logistics can be recovered
at the liquefier site

Specific energy : **7-8 kWh/kg** of liquid for large liquefier
(> 30 tpd, pre-cooling included)

H2 cycle liquefier



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Air Liquide H2 liquefier in Las Vegas

Air Liquide

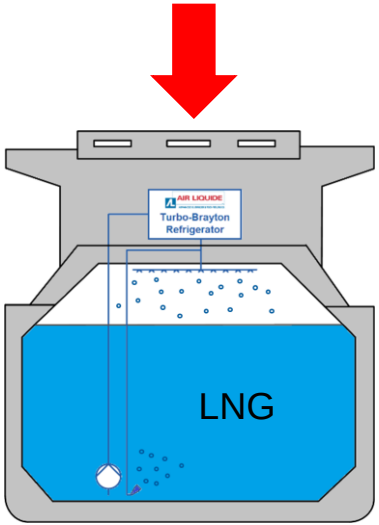
Steam Methane Reformer

Hydrogen Liquefier (30 tpd)

Liquid H2 Storage (1800 m3)

CO2 emissions compensated by biogas production

Reliquefaction of LNG aboard ships with the turbo-Brayton



Principle

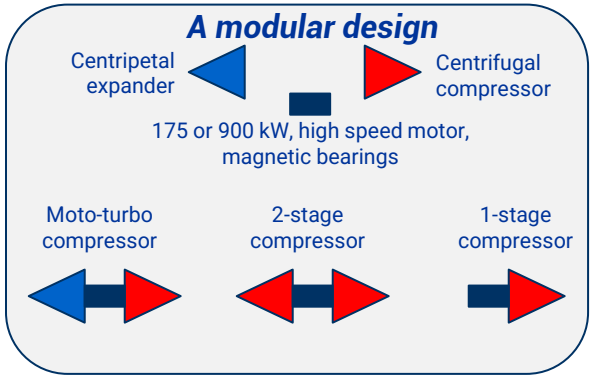
Bunker vessels

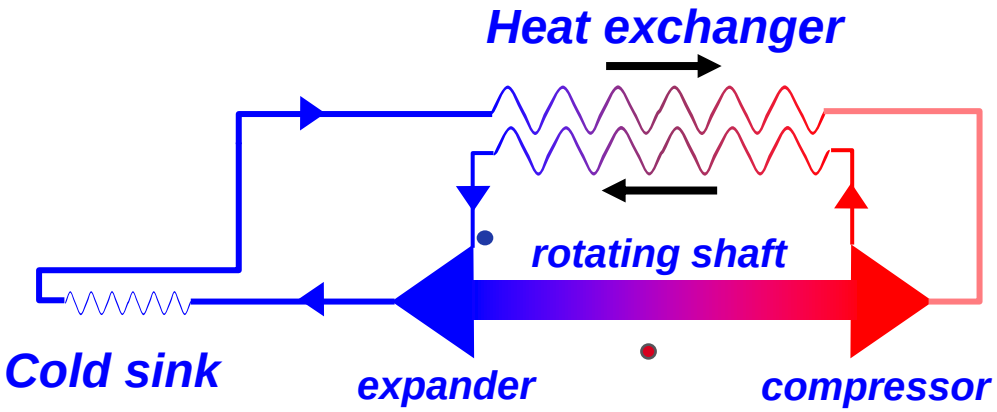
Newbuilt / Retrofit LNG Carriers (174 000 m3)

FSRU

200+ Turbo Brayton (TBF) already sold since 2015

From LNG to HTS with the turbo-Brayton





From 1 to 8 turbomachines: from 175 kW to 8000 kW

Product range	TBF-175	TBF-350	TBF-700	TBF-1800-1.5	TBF-1800-2.1	TBF-1800-2700
Expected LNG flow @113K	0.2 t/h	0.5 t/h	1 t/h	1.5 t/h	2.1 t/h	Up to 3 t/h
Theoretical cooling power @65K	17 kW	35 kW (*)	70 kW	90 kW	90 kW	130 kW
Theoretical cooling power @~20K	4 kW	8 kW	17 kW	45 kW	45 kW	65 kW





TB 1400 successfully tested with 8 turbomachines
Well suited for High Temperature Superconductivity
Can provide more than 35 kW @ ~ 25-30K
Air Liquide
Air Liquide

Breaking news : **July 16, 2024 :18th anniversary of 3 turbo-Brayton in orbit**

Technologies required for the energy transition :

On-board Cryogenic Storages for H2-powered vehicles

For more information, see : *Cryogenic Tests of an Airborne Liquid Hydrogen Tank in a Manned Aircraft in the Heaven Project*, D. Favier and L. Jeunesse, ICEC-ICMC 2024

LH2 in the Shipping industry : for transportation or propulsion

SUISO FRONTIER built by Kawasaki
- 1250 m3 of liquid H2
- January 2022 between Australia and Japan

- Other projects in progress like Energy Observer 2 for propulsion, in partnership with Air Liquide

Energy Observer

Future LH2 tanker
4 x 40 000 m3

What about new applications ?

HTS cables for offshore power transmission lines

HTS cables already exist in the kilometric range

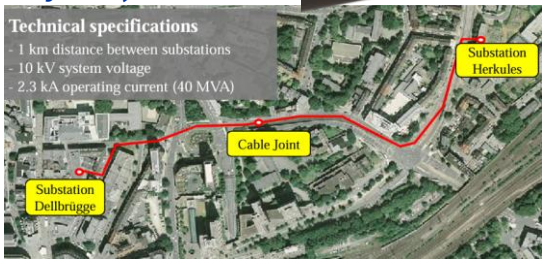
The O&G industry can lay down insulated LNG piping on the seafloor (ϕ > 400 mm)

1 MW @ 65 K with turbo-Braytons for 80-100 km, >1 GW

without intermediate station

LIPA (600 m, 640 MW AC)

AMPACITY (1 km, 7 years)



Might be much cheaper & efficient than conventional offshore or onshore power transmission lines

Off-shore wind power : storm warning on rare earths!

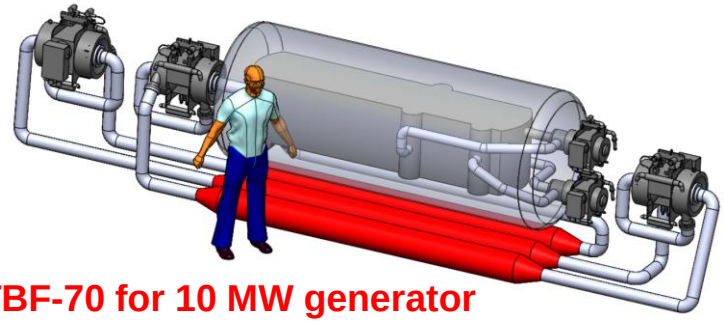
600 à 1200 GW / 2050
66 / 2020 **20X**

7 t rare earth / 10 MW ⇒ 800 000 tons
⇓
Critical Raw Material Act(EU)
WindPower Europe, April 2023

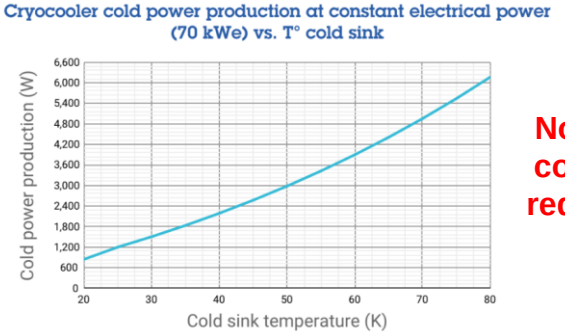
EcoSwing (2021) :
3,4 MW, 400 W @ 25K, REBCO
cooled by commercial GM coolers
(Sumitomo)

The EcoSwing Project, by T Winkler and al., in CEC-ICMC 2018

far less rare earths needed
lighter nacelle (TCO)

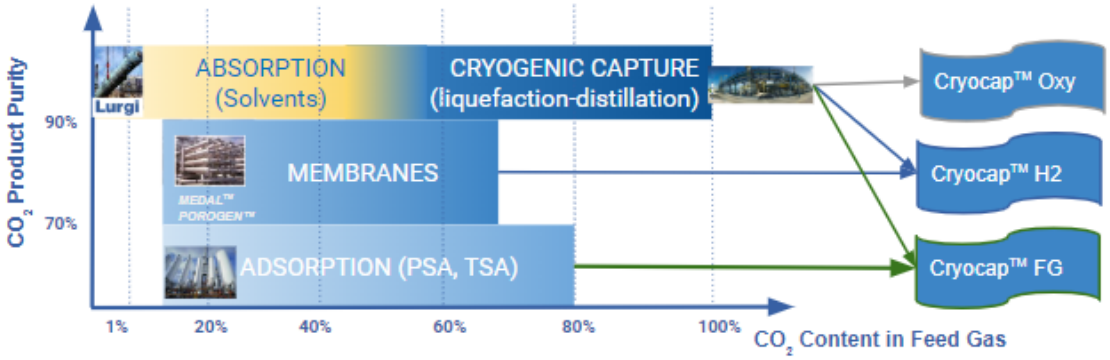


TBF-70 for 10 MW generator
based on marinized turbo-Brayton technology



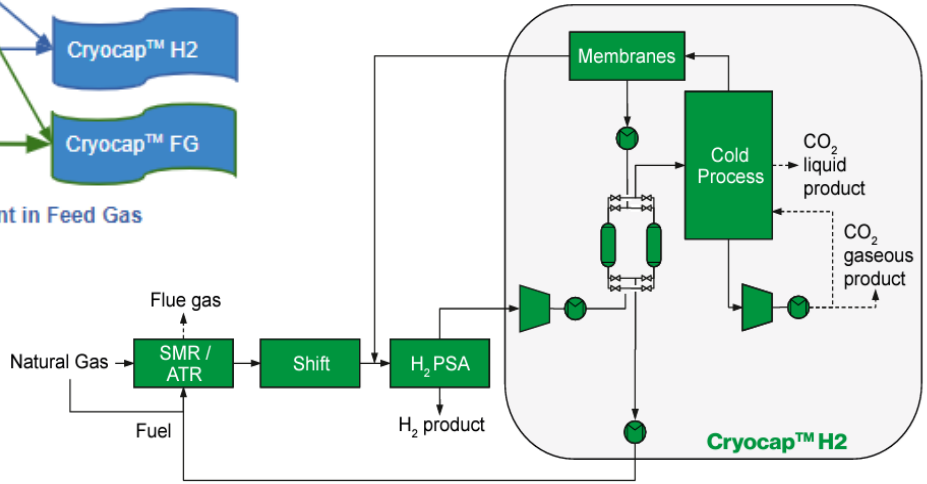
No pre-cooling required

Cryogenic distillation is well suited for CO2 concentration > 40%



-50°C < T < -20°C

Cryocap ™ H2



Captured CO2 can be used for :

- Food industry
- E-fuel synthesis
- Sequestration

All require ultra-purity (<ppm level)

« warm » cryogenics but similar technologies and competencies

Removal of 100 000 tons of CO2 per year with Cryocap ™ for blue H2

Conclusions

In a society which is becoming more and more electrical, cryogenics is now expected to play a major role, given its potential for :

- Electrical energy generation and transmission, with superconductivity
- Chemical energy storage and transportation, with cryogenic energy carriers
- Capture, purification and transportation of CO2

All technology bricks are there

Powerful and industrial cryogenic refrigerators and liquefiers are available on a wide range of temperatures & cooling powers

Dear cryogenist fellows: it is now our turn!